The LHCf (LHC forward) experiment
~ a collider experiment dedicated for ultra-high-energy cosmic-ray physics ~

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Very-high-energy cosmic ray spectrum

$10^{17}$ eV CR (fixed target) $\leftrightarrow$ cm energy at LHC (7+7 TeV)

$>10^{15}$ eV: detected with air-showers, but many unknowns.
1. Inelastic cross section

- If large $\sigma$: rapid development
- If small $\sigma$: deep penetrating

2. Forward energy spectrum

- If softer: rapid development
- If harder: deep penetrating

3. Inelasticity $k$

$$\frac{1-E_{\text{leading}}}{E_0}$$

- If large $k$: rapid development
- If small $k$: deep penetrating
Hadron interaction model - major source of uncertainty -

LHC data is expected to reduce this uncertainty
What should be measured?

Multiplicity and energy flux at LHC 14TeV collisions
pseudo-rapidity; \( \eta = -\ln(\tan(\theta/2)) \)

Most of the energy flows into very forward
The LHCf Collaboration


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Detector Location

LHCf Detector (Arm#1)

Two independent detectors at either side of IP1 (Arm#1, Arm#2)

LHCf Detector (Arm#2)

96mm

Beam
Neutral particles
Charged particles (+)
Beam pipe
Charged particles (-)

TAN - Neutral Particle Absorber -
transition from one common beam pipe to two pipes
Slot: 100mm(w) x 607mm(H) x 1000mm(T)
**LHCf Detectors**

**Imaging sampling shower calorimeters**

- Two independent calorimeters in each detector (Tungsten 44r.l., $1.6\lambda$, sampling with plastic scintillators)
- 4 position sensitive layers distributed in the calorimeters

**Arm#1 Detector**
- $20\text{mm} \times 20\text{mm} + 40\text{mm} \times 40\text{mm}$
- 4 XY SciFi+MAPMT

**Arm#2 Detector**
- $25\text{mm} \times 25\text{mm} + 32\text{mm} \times 32\text{mm}$
- 4 XY Silicon strip detectors
Detector photos

Arm#1 Detector

Arm#2 Detector

290mm  90mm
Event category of LHCf

- **Single hadron event**
- **Single photon event**
- **Pi-zero event** (photon pair)
Expected Results at 14 TeV Collisions
(MC assuming 0.1nb⁻¹ statistics)

single photon

γ Energy Spectrum of 20mm square at Beam Center

DPMJET3
QGSJET
QGSJETII
SIBYLL

Single photon at different η

π⁰ Energy Distributions

DPMJET3
QGSJET2
QGSJET1
SIBYLL

Detector response not considered

π⁰

Single neutron
# Summary of Operations in 2009 and 2010

## With Stable Beam at 900 GeV
- Total of 42 hours for physics
- About 100 k showers events in Arm1+Arm2

## With Stable Beam at 7 TeV
- Total of 150 hours for physics with different setups
  - Different vertical position to increase the accessible kinematical range
  - Runs with or without beam crossing angle
  - \( \sim 400 \) M shower events in Arm1+Arm2
  - \( \sim 1 \) M \( \pi^0 \) events in Arm1+Arm2

## Status
- Completed program for 900 GeV and 7 TeV
- Removed detectors from tunnel in July 2010
- Post-calibration beam test in October 2010
- Upgrade on-going to more rad-hard detectors for 14TeV in 2014

![Arm1 \( \pi^0 \) stat.](chart.png)
EM shower and $\pi^0$ identification

Event sample in Arm2

- A $\pi^0$ candidate event
- 599GeV & 419GeV photons in 25mm and 32mm tower, respectively
- $M = \theta \times \sqrt{E_1 \times E_2}$

Longitudinal development

- Small Cal.
- Large Cal.

Lateral development

- Silicon X
- Silicon Y

Invariant mass of photon pairs

Comparison with models, coming soon
Photon spectra at 7TeV collisions

(Published in PLB, ArXiv:1104:.5294v2 [hep-ex])

✓ The simplest photon spectra by Arm1 & Arm2 at common rapidity
✓ \( N_{\text{ine}} = \sigma_{\text{ine}} \times \text{int}(Ldt) \) (\( \sigma_{\text{ine}} = 71.5\text{mb} \) assumed; consistent with recent ATLAS result)
✓ e/h shower separation based on the longitudinal shower development

\[ \Rightarrow \text{Combined & compared with MC models} \]
• None of the models nicely describe the LHCf data in the whole energy range (100 GeV – 3.5 TeV).
• Very big discrepancy in the high energy region (>2 TeV)
• Significant improvement of the models is possible with model developers
Upgrade for 14TeV

for rad-hardness

higher luminosity is expected in the 14TeV runs

for improvement of energy reconstruction

Silicon layer positions in Arm2 detector

Energy reconstruction with the Si layers is also useful!
Analysis of the Si layers (my ongoing work)

- Energy reconstruction with the Si data
  - complementary to that with the scintillators
  - for separation of multi-hits in 1 tower

- It requires
  - calibration (ADC count -> energy deposit -> incident energy)
  - correction for the saturation effects (only for high-E events)

A (gain calibration)
Test beam at SPS in 2010
- 100, 150, 175, 200GeV e⁻
- comparison with MC
- averaged over energies

=> Gain: 42.8 ADC/MeV, +0.5%-1.0% (sys.)

B (incident E reconstruction with MC)
Energy of incident γ: 50, 100, 200, 500GeV, 1, 2, 3TeV

errors: sys. from diff. methods
dE on Si => E with ~3% precision

Refinement of the methods is ongoing
Summary & Prospects

- LHCf is a cosmic-ray dedicated experiment in LHC
- DAQ in LHC sqrt(s) = 7 TeV pp collisions completed

Analyses
- Photon spectra at sqrt(s) = 7TeV (published in PLB)
- Photon spectra at sqrt(s) = 0.9 TeV
- $\pi^0$ spectra
- Impact on EAS
- Energy reconstruction improvement
- $P_T$ spectra, Hadron spectra, test for LPM effect
- Correlation with central production (joint analysis with ATLAS)

Measurements
- $LHC\ sqrt(s) = 14\ TeV\ pp$ (scheduled after 2014; rad-hard upgrade on going)
- in study: LHC p-Pb (2012?), possibility in the other colliders
- N-p, N-N, N-Fe (N; Nitrogen) in future?

Still many dishes to enjoy!!
Backup
Very forward – connection to low-x physics (slides by Y. Itow)

- Very forward region: collision of a low-x parton with a large-x parton
- Small-x gluon become dominating in higher energy collision by self interaction.
- But they may be saturated (Color Glass Condensation)

Naively CGC-like suppression may occur in very forward at high energy

→ However situation is more complex (not simple hard parton collisions, but including soft + semi-hard)
Physics of MCs (K. Werner, EDS09, CERN)

**EPOS, QGSJET**

Multiple scattering of Gribov-Regge type

- Semihard “Pomerons”: soft - pQCD - soft
- Remnants
- Partonic final state => strings

**SIBYLL**

- no Remnants
- “main” scattering => qq-q strings
- further scatterings => strings between gluon pairs
Nonlinear effects in MCs

Nonlinear effects in QGSJET

Pomeron-Pomeron coupling

□ Summing all orders
□ No energy conservation
□ (in EPOS full energy conservation, but effective treatment of nonlinear effects)

Nonlinear effects in EPOS

To include rescatterings of partons, fit parton-ladder\(^1\) as \(\alpha (x^+)^\beta (x^-)^\beta \), modify as

\[ \alpha (x^+)^\beta (x^-)^\beta + \varepsilon, \]

Effect can be summarized by a simple positive exponent \(\varepsilon\)

(dep on \(\log s\) and \(N_{\text{particip}}\), incorporating saturation)

\(^1\)Imaginary part of the corresponding amplitude in \(b\)-space

\(^2\)\(x^+, x^-\): light cone momentum fractions of the first ladder partons

Nonlinear effects in SIBYLL

Saturation scale obtained from

\[
\frac{\alpha_s N_c}{Q^2} \times \frac{1}{N_c^2 - 1} \frac{xG}{\pi R^2} = 1
\]

□ Used as cutoff

Non-linear effects are implemented in a phenomenological manner

all slides are by

K. Werner, EDS09, CERN
air-shower development: $X_{\text{max}}$
FrontCounter

- 2 fixed Front Counters installed in front of Arm1 and Arm2
- They will not move with Arm1 and Arm2
- segmented in 2 x- and 2 y-slices
- Very useful to check the beam quality
Acceptance

$\pi^0$

Photon at $\sqrt{s} = 14$ TeV pp collision
2010 operation at $\sqrt{s}=7\text{TeV}$

Low luminosity ($L=2\sim10\times10^{28}\text{cm}^2\text{s}^{-1}$)
($1\sim2.5\times10^{10}\text{ppb}, \beta^* = 2\text{m}, N_b = 1\sim4$)
No crossing angle

High luminosity ($L=3\sim20\times10^{29}\text{cm}^2\text{s}^{-1}$)
($1\times10^{11}\text{ppb}, b^* = 3.5\text{m}, N_b = 1\sim8$)
100$\mu$rad crossing

Low luminosity:

- $1\sim2.5\times10^{10}\text{ppb}$
- $\beta^* = 2\text{m}$
- $N_b = 1\sim4$
- No crossing angle

High luminosity:

- $1\times10^{11}\text{ppb}$
- $b^* = 3.5\text{m}$
- $N_b = 1\sim8$
- 100$\mu$rad crossing

Graph showing the number of showers over time for 4/1 to 7/22.

Graph showing the number of events over time for 3/21 to 7/25.
Particle ID

- EM and hadronic shower separation based on the longitudinal shower development
- $N_{\text{photon}}/N_{\text{hadron}}$ ratio will give a good information for model
- Response of detectors to hadrons in study
Game with modified meson spectrum

Play within the model uncertainty
Play within the LHCf error